CONSTRAINS ON THERMAL EVOLUTION OF MARS FROM RELAXATION MODELS OF CRUSTAL AND TOPOGRAPHIC DICHOTOMY, A. Guest and S. E. Smrekar, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA; alice.guest@jpl.nasa.gov, ssmrekar@jpl.nasa.gov.

Introduction: The early thermal evolution of Mars is largely unconstrained. Models such as degree one convection [1,2,3], plate tectonics [4], and a transition to stagnant lid [5] have been proposed to explain formation of the dichotomy, the Tharsis rise, crustal production, and dynamo evolution. Here we model both the early deformation of the dichotomy and the long-term preservation as a means of examining the plausibility of a range of early thermal evolution models. Constraints include the preservation of crustal thickness and topographic differences between the northern and southern hemispheres and the geologic history of the dichotomy [6]). Our previous modeling indicates that the lower crust must have been weak enough to allow for relaxation early on, but the Martian interior had to cool fast enough to preserve the crustal difference and the associated topographic difference (~5 km) over approx. 3-3.5 Gyr [7].

Concept: We attempt to constrain the early thermal evolution of Mars by testing the effect of temperature evolution in the mantle and lithosphere on the relaxation of the Martian dichotomy. We start with an initial topography of Martian dichotomy that is slightly higher and steeper than present topography. Then we apply the temperature evolution as determined by a coupled thermal-magmatic stagnant-lid numerical model [8] from 4-3 Gyr to our relaxation model and study the effect of temperature cooling on dichotomy relaxation. This thermal model [8] predicts the production of the crust of the observed thickness ~62 km [9] within the 0.5-1 Gyr [10]. We also vary mantle temperatures and test dry/wet rheologies in order to determine the limiting temperature evolution of a stagnant lid model that would allow for a preservation of Martian dichotomy.

Geologic data: We use geologic observations and topography in the Ismenius region (NW of the Isidis basin and E of Arabia Terra) to be compared with our model. The Ismenius region seems to be the best-preserved section of the dichotomy boundary, even though it shows signs of the early relaxation: the boundary consists of a steep scarp with an elevation of 2.5 km and a slope 20-23 degrees across a series of fractures. Strain across the boundary is at least 3.5% [6].

Technique: We use two techniques for studying the relaxation of the Martian dichotomy: finite-element modeling and semi-analytical modeling. Finite-element modeling allows for detailed study of the evolution of stresses and strains related to the relaxation of the Martian dichotomy, but is computationally demanding and thus doesn't allow for testing a wide range of parameters over long time periods. Semi-analytical modeling is very efficient, however, the evolution of stresses and strains (and thus viscosity) must be set a priori.

Finite-element model: Our 2-D plain-strain finite-element model uses an elasto-visco-plastic rheology and consists of two materials – crust and mantle. The starting geometry (Fig. 1) places the highlands 5 km higher than the lowlands. Assuming a crustal density of 2900 kg/m3, and a mantle density of 3300 kg/m3, we include a 24.2 km thick crustal root below the plateau to produce isostatic compensation [6]. The width of the dichotomy boundary is 143 km and the average slope, smoothed using a cosine function, is 2 degrees. We use wet diabase [11] and wet olivine [12] as a representative for the rheological behaviour of the crust and mantle, respectively. We use a Mohr-Coulomb criterion for plasticity, with cohesion of 9 MPa and friction of 40 degrees. The size of our mesh is 1500 km horizontally by 1000 km vertically and contains 5830 elements. The bottom of the box is fixed, the sides have fixed horizontal displacement and zero vertical shear stress, and the top is a free surface. The initial condition is hydrostatic pressure.

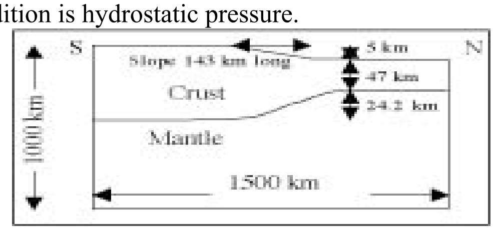

Fig. 1: Sketch of the model. Not to scale.

Semi-analytical solution: Assuming an incompressible viscous fluid, the equilibrium and constitutive equations can be solved semi-analytically in the frequency domain using a linearization that requires the boundary relief to be small compared with the wavelength and the layer thickness. The horizontal variations of the stress and velocity are transformed to the frequency domain using the Fourier transform. The vertical differences are numerically integrated thus allowing for variations of viscosity with depth. The viscosity variations are input in the model a priori and should represent the effective viscosity at a given depth. Using the Laplace transform solves the time evolution.

The viscosity evolution with time is hard to predict since viscosity is dependent on strain rates, stresses, and temperature. We can estimate the strain rate from rheological creep laws because creep strain is the most significant strain in the relaxation process. In order to predict stress evolution, we use stresses from our finite-element model and scale them according to the amount of relaxation of the highlands altitude and change in the dichotomy slope.

Temperature: The temperature evolution (first temperature model TM1) in the lithosphere is shown in Fig.2 to the depth of 150 km. Below the base of the lithosphere, which is defined by temperature 1710 K at 110 km at 4 Gyr and by temperature 1660 K at 145 km at 3 Gyr, the temperature remains constant. The temperature is based on the nominal model of [8]. We also test the effect of a 200 K cooler mantle temperature (second temperature model TM2). In this case, the heat conduction equation is solved with the same parameters as in the [8], but the mantle temperature is changed.

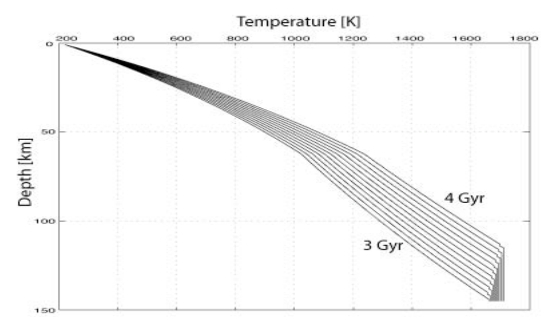

Fig. 2: Temperature evolution in the lithosphere from 4 to 3 Gyr based on model of [8].

Results: We ran the finite-element model where dry rheology and TM2 were used. This model allows for the preservation of the Martian dichotomy with a minimal relaxation on the surface.

We tested weaker rheologies (wet rheology and TM2 = model A, wet rheology and TM1=models B ,C, and dry rheology and TM1=model D) by the semi-analytical solution. The results show that when dry rheology is used (model D), the relaxation of Martian dichotomy is negligible. When wet rheology is used, the amount of relaxation is dependent on the temperature and stress in the lower crust (models B and C differ by stress in the lower crust). The dependence on the temperature and stress can be expressed via viscosity. Thus, when viscosity in the lower crust rises from 10^18 Pa s at 3Gyr to 10^21 Pa s at 4 Gyr, the Matian dichotomy is relaxed beyond present observations. If the viscosity rises from 10^20 (A), 10^19 (B), or 3x10^18 (C) Pa s at 3 Gyr to 10^24 (A), 7x10^22 (B), or 10^22 (C) Pa s at 4 Gyr, only the edges of Martian dichotomy are relaxed (Fig. 3).

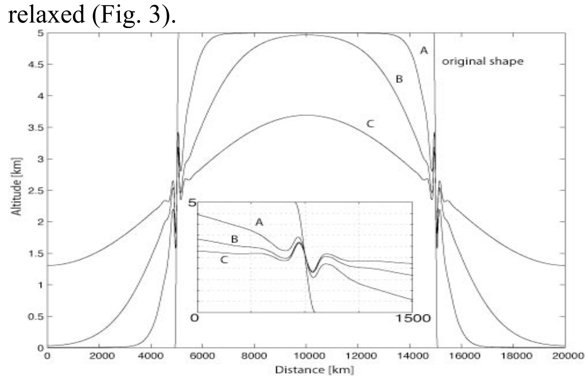

Fig. 3: Topographic evolution of Martian dichotomy from 4 to 3 Gyr for models A, B, and C. The rectangular enclosure shows the detail around the dichotomy boundary.

Discussion and Conclusions: The nominal stagnant lid model (wet rheology and TM1) of thermal evolution of Mars [8] allows for the preservation of the Martian dichotomy if the viscosity in the lower crust ranges 10^18-10^19 Pa s at 3 Gyr and 10^22-10^23 Pa s at 4 Gyr. The relaxation of the edges of the Martian dichotomy agrees with the geological observations in the Ismenius region [6,7,10].The thermal model is non unique and the input parameters may be varied. The presence of dry rheology would preserve the Martian dichotomy with a negligible relaxation, however, our model cannot assure that such conditions would lead to the production of the observed crustal thickness on Mars within 0.5-1 Gyr. Since the geological observations show 3% strain on the surface near dichotomy boundary [6,10], these strains would have to be produced later in the evolution of Martian dichotomy [13]. Other models of thermal evolution, e.g., a model considering the early stage of plate tectonics [5], and a model including the magmatic overturn [14], will be tested to study their effect on the relaxation of the Martian dichotomy.

References: [1] Breuer, D. et al. (1997) EPSL, 148, 457-469. [2] Breuer, D. et al. (1998) GRL, 25, 229-232. [3] Zhong S. and Zuber M. T. (2001), EPSL, 189, 75-84. [4] Sleep N. (1994) JGR, 99, 5639-5655. [5] Lenardic, A. et al. (2004) JGR, 109, 10.1029/2003JE002172. [6] Smrekar S. E. et al. (2004) JGR 109, 10.1029/2004JE002260 [7] Guest, A. and Smrekar S. E. (2004) LPSC 2004. [8] Hauck S. and Phillips R. (2002) JGR 107, 10.1029/2001JE001801. [9] Neumann G. A. (2004) JGR 109, 10.1029/2004JE002262. [10] McGill G. E. and Dimitriou A. M. (1991) JGR 95, 12595-12605. [11] Mackwell, S. J. et al. (1998) JGR 103, 975-984. [12] Karato, S-I. and Wu, P. (1993) Science, 260, 771-8. [13] Watters, T. (2003) JGR, 108, 10.1029/2002JE001934. [14] Zaranek S. EPSL, 224, 371-386.